AUV Navigation and Self-Motion in Shallow Water

Samuel Smith

Department of Ocean Engineering

Florida Atlantic University

Boca Raton, FL 33431

(office) 561-367-3066   (fax) 561-367-3885   smith@oe.fau.edu

Edgar An

Department of Ocean Engineering

Florida Atlantic University

Boca Raton, FL 33431

(office) 561-367-2459   (fax) 561-367-3885   ean@oe.fau.edu

LONG-TERM GOALS

The general objective is to investigate basic and applied problems associated with the efficacious reconnaissance of littoral waters in support of mine warfare and oceanographic tasks. An underlying goal is to strive for cost-effective means to solve these problems.

OBJECTIVES

We wish to address the problems of navigation and self-motion of small AUVs in shallow water. Specific objectives are to characterize the performance of the navigation system and Kalman filter in shallow water and energetic environments; to characterize the self-motion properties of small AUVs operating in shallow water in relation to sea-state and depth; to evaluate the suitability of small AUVs as platforms for imaging sonars; to provide smoother and more accurate estimates of vehicle self-motion in energetic environments.

APPROACH

Navigation

Multiple sensor data fusion approach which asynchronously combines DGPS, LBL, SBL and DVL sensor outputs into an extended Kalman filter framework is proposed. On the surface, the use of DGPS provides a drift free error on the order of 1-2 meters given well-distributed satellite geometry. During underwater missions, the preplaced transponder nets provide drift free error on the order 2-5 meters, although the update rate can be less than 1 second when the range exceeds 2km. For docking and rendevous operations, local area navigation requires position and velocity updates at higher rates in order to control to precise position commands, and a DVL-aided INS will be used to provide the higher frequency updates. The extended Kalman filter will be developed by the Naval Postgraduate School, and then ported to the Ocean Explorer AUV by FAU. The initial software will run on VxWorks using a 680x0 board. Once the system is validated the software will be ported to a PC-104 Pentium board which will be configured as a node on the LonTalk network. At-sea tests will be conducted to validate and characterize the performance of the integrated navigation system with DVL, DGPS and LBL individually and in combination.

Report Documentation Page		*Form Approved* *OMB No. 0704-0188*

Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.

1. REPORT DATE **30 SEP 1997**	2. REPORT TYPE	3. DATES COVERED **00-00-1997 to 00-00-1997**
4. TITLE AND SUBTITLE **AUV Navigation and Self-Motion in Shallow Water**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Florida Atlantic University,Department of Ocean Engineering,777 Glades Road,Boca Raton,FL,33431**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**5**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Self-Motion

The Ocean Explorer (OEX) vehicles have built-in RDI DVL (1.2MHz), 3-axis rate gyros, accelerometers that provide information about the vehicle motion. To correlate the motion with sea-states, an IO S4 current meter will be used which provides wave height, frequency and direction. The wave data are then correlated with the vehicle's attitudes, rates and accelerations at different vehicle depths and orientations with respect to dominant wave direction. The DVL mounted on the OEXs will provide the current velocity for the bottom part of the water column. An additional upward-looking ADCP will be mounted on the OEXs which altogether will provide complete water column measurements of current shear. A sea-bottom mounted ADCP will be used to provide a baseline reference to validate the AUV data. A series of surveys at various depths and relative heading to waves will be performed to characterize the self-motion and current shear. In addition self-motion measurements will be made using the DTRC (MAST) facility to calibrate the sensors and models. Extensive measurements of vehicle self-motion will be conducted using the existing Watson gyro and accelerometer units installed in the Ocean Explorer vehicles with sea-state correlation given by the current meter and ADCP. An analysis and characterization of the vehicle self-motion for the purpose of sensor compensation will be performed.

WORK-COMPLETED

Navigation

The DVL and DGPS have been characterized in terms of their biases, and Precision Nav compass has been characterized in terms of its bias and local magnetic interference. A heuristic fuzzy position estimator has been developed and implemented on the Ocean Explorer. The heuristic estimator performs asynchronous data fusion of all sensor measurements based on their relative confidence levels, and then nonlinearly combines the fused information with the INS estimates via fuzzy filtering techniques. In parallel, an extended Kalman filter has been developed for 2D AUV navigation problems.

Self-Motion

Sensor noise from the Watson gyros have been characterized in terms of biases and rms fluctuations. A large set of controlled vehicle motion data (50 individual missions) were collected at the NSWC-DTRC over a 4 day period in April, 1996. The data set consists of the vehicle motion collected in head/following and beam sea conditions under waves of different frequencies and heights. The vehicle motion and wave data were characterized and correlated between the vehicle attitudes/rates/accelerations and wave frequencies under different wave encountering heading conditions. Off-shore measurements of AUV self-motion were collected from approximately ten separate missions. A complete set of hydrodynamic coefficients was obtained through Doug Humphreys, and numerical simulation based on the coefficients was implemented. Comparative results between measurements and simulation were found to be acceptable.

RESULTS

Detailed results of navigation and self-motion studies can be found in the references. The following provides only a selected portion of the results.

Navigation

Figure 1 presents results of a 3-hr mission covering 15km transect. Sporadic fixes can be seen in the figure which corresponds to the OEX surfacing maneuvers. Among these fixes, maximum discrepancy between the position estimator and GPS fixes was found at location [-50 east, 150 north], and also it can be seen that the position estimator responds less to these GPS fixes, but much more to the DGPS fixes obtained immediately afterwards. By observation, the discrepancy was approximately 100m since the last update (6 legs of transect away $\approx$ 3300m), and thus the error was approximately 3%. It should be noted that 100m is within the limit of the GPS error deviation, and the result suggests that accurate navigation does not necessarily require frequent surfacing, as expected from previous discussion. During underwater navigation, significant error comes from heading bias in the Precision Nav compass due to internal magnetic interference, which is on the order of 1-5 degrees in magnitude. To account for the heading bias, an extended Kalman filter with DGPS fixes as the sole reference heading was implemented. Results indicate that the heading bias could be learned during missions, thus providing dynamic deviation characteristics to the AUVs. Convergence times on order of 2-3 minutes were found to be typical, and are considered reasonable for calibrating the initial heading mis-alignment. Further work will be carried out in modeling the sinusoidal nature of the heading error, which is expected to significantly improve the navigation performance. An asynchronous version of extended Kalman filters was also developed which no longer requires a fixed number of measurements between updates.

Self-Motion

Based on the results collected at the DTRC, Figure 2 shows the normalized standard deviations of pitching, rolling and yawing motion as a function of encountering frequency as observed along the *forward* axis under head, follow and beam-sea conditions. This arrangement provide useful insights into the validity of the linear vehicle response assumption with respect to wave amplitude. In each of these figures, the first, second and third columns of subplots are associated with the head, follow and beam-sea conditions respectively, and each row indicates the standard deviation for the specified motion variable. In each of these plots, 'x' and '+' markers denote regular waves of 16" and 32" wave height respectively, and 'o' markers denote those cases where large motion excursions (either submergence or emergence) were observed. It should be mentioned that these wave and vehicle motion data were carefully selected so that the vehicle motion and sea-states could be properly correlated at *similar* depths. Among the missions carried out at the DTRC at shallower depth (1.5m as measured from the bottom hull), significant surges were observed in pitching and rolling motion, and thus their spectral profiles were dominated by the slow-moving surge components, and so were their standard deviations. These results suggest that the OEX is currently unsuitable to maintain accurate depth-following within this range under sea-state 2 and higher, unless the vehicle dynamics can be stiffened. Possible choices include increasing the cg/cb separation, better fin and controller re-design. Nevertheless, these choices need to be verified with further self-motion test results. Standard deviation results reveal that the existing OEX is capable of producing approximately 3 degrees (peak-to-peak) pitch, 0.7 degree (peak-to-peak) roll and 0.6 degree (peak-to-peak) yaw at $2m$ depth in the head-sea condition when the encountering wave frequency is close to $1Hz$ (see Figure 2). Thus its motion profile can be tailored by choosing proper vehicle speed and heading if the wave characteristics can be measured on-board. These choices are realistic as typical missions do not impose harsh constraints on vehicle speed as long as its duration is supported by on-board batteries. Also, high-level mission planner can accomodate appropriate heading envelopes such that self-motion is minimized.

IMPACT/APPLICATIONS

The navigation study has major implications on providing a low-cost, high-precision navigation solution for AUV docking and mine countermeasure operations, whereas the self-motion study has important implications on characterizing stability of small AUVs in shallow water for mine counter-measure applications.

TRANSITIONS

The self-motion results are being studied for designing an AUV docking station in shallow-water, and the vehicle motion due to wave loading provides important quantitative error margins for determining the docking criteria. In addition, the results will be used to generate wave-induced motion coefficients of small AUV motion in shallow-water as part of an FAU ONR-funded project. The hydrodynamic coefficients and numercial simulation of the Ocean Explorer are being used in another ONR-funded MURI project.

RELATED PROJECTS

- Autonomous Oceanographic Sampling Network Development (ONR, 1/1/96-12/31/97).

- Synoptic Data Collection with Multiple AUVs (ONR, 1/1/96-12/31/97).

- Enhancing AUV Operational Capabilities: Hovering, Rendevous and Docking (ONR, 1/1/96-12/31/97).

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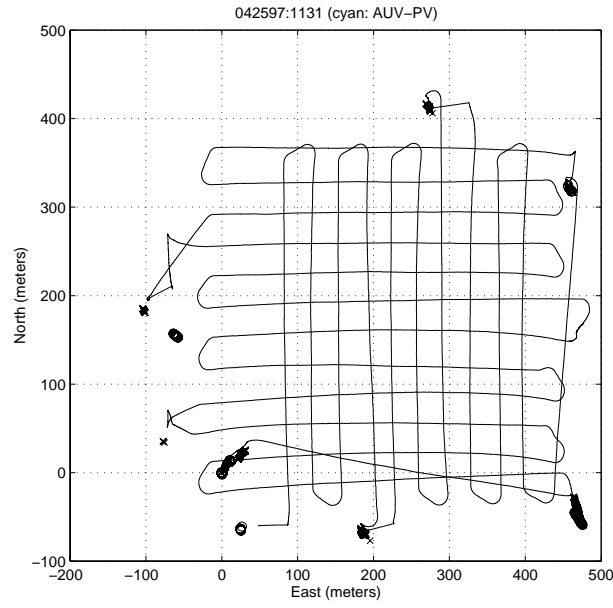
Figure 1: Heuristic position estimator and GPS outputs. Solid line: heuristic position estimator output, and dash line: dead-reckoned output. 'X' and 'O' represent differential and regular GPS fix respectively.
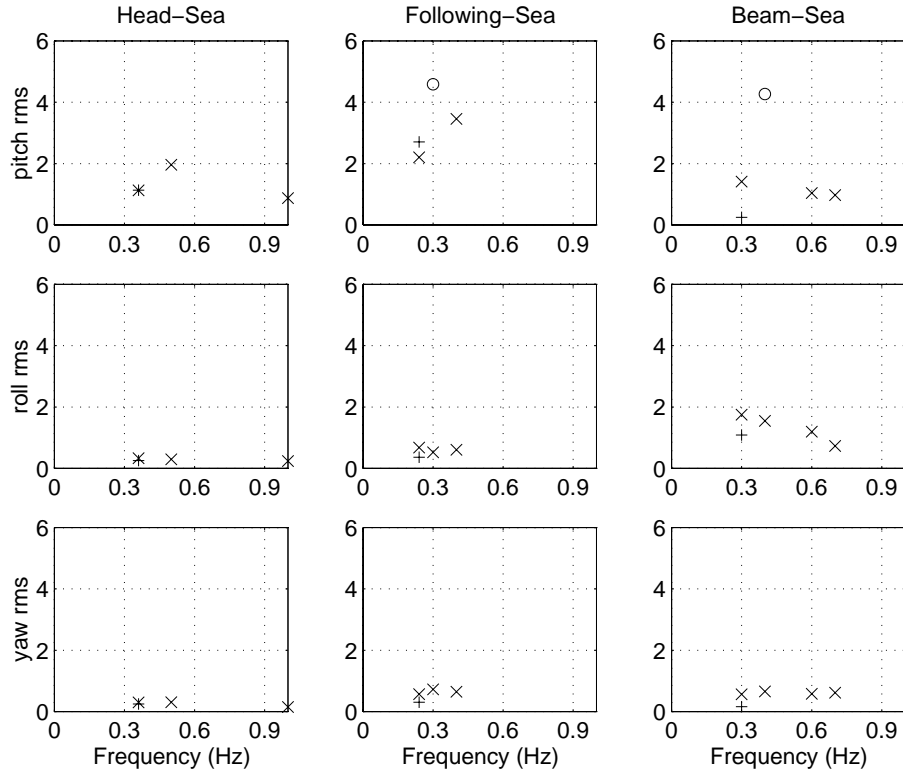

Figure 2: Normalized standard deviations of pitching, rolling and yawing motion as a function of encountering frequency under head, follow and beam-sea conditions. See text in Section 4.2 for more detail.